Determination of Thermal Properties of New Zealand's soils and investigations of external factors influencing the near surface low-temperature geothermal resources.

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ABSTRACT

Shallow geothermal, near-surface rocks and soils provide low carbon renewable energy for heating and cooling of buildings. The amount of heat able to be stored in the rock and soil is dependent on the thermal properties of the matrix, porosity / permeability, and moisture content. Local climatic factors, air temperature and rainfall influence the near surface conditions.

Utilising low-temperature geothermal resources is not new, it is common in Europe and North America but with growing interest in many nations as the world focus's on "greener" low carbon technologies. New Zealand is developing an understanding of how these technologies might be applied in our nation, with an understanding of our near-surface low-temperature geothermal resources.

This paper presents data from two shallow ground temperature monitoring boreholes, one in the North Island, and one in the South Island of New Zealand. Time-series and temperature profile data are used to calculate apparent thermal diffusivity. The computed values are compared to laboratory measurements made on collected soil samples.

Data from 62 shallow (< 1 m) ground temperature profiles from New Zealand climate stations are also analysed for thermal properties of varying soil types around New Zealand. Apparent thermal diffusivity values of New Zealand soils range from 0.17 mm^2s^{-1} to 1.6 mm^2s^{-1}, with lower diffusivities generally found in the North Island.

1. INTRODUCTION

Solar radiation penetrates the Earth's surface warming the ground beneath. This near-surface energy resource can be utilised to provide heating and cooling to buildings, using geothermal heat pumps (ground-source heat pumps). Ground temperatures at depth remain relatively constant throughout the year, potentially providing a stable source for heating in the winter months, and cooling in the summer months. New Zealand covers a wide range of latitudes, stretching from 35°S to 47°S. Its climate, therefore, varies from warm subtropical in the north to cool temperatures in the south, with severe alpine conditions in the mountainous areas, both in the North Island and the South Island. Average daily winter air temperatures can plummet to -5 °C while summer temperatures can reach temperatures of more than 35 °C. Seward et al (2013) outlines a small desktop study of regional seasonal temperature variations and the heating and cooling demand for New Zealand. Areas of extreme air temperature variations and therefore highest need for winter heating and summer cooling are found in the South Island and central North Island.

Ground source heat pump technology utilises ground loops in the near-surface for exchanging heat, extracting warmth in the winter months and depositing heat in the summer. Closed ground loop configurations can generally be horizontal, where piping is laid in shallow (1-5 m deep) trenches, or vertical, where pipes are installed in a series of boreholes. Open loops can utilise surface or sub-surface aquifers, in suitable settings. Generally, for closed loop systems, it is cheaper to install horizontal loops, provide the land area is sufficient. However, the shallower ground temperatures are greatly influenced by local climatic conditions. Fluctuations in seasonal and daily air temperature, rainfall, and sunshine hours all affect the ground temperatures. These local climatic factors induce both daily and seasonal temperature variations in the ground. Moisture levels, or water content, also affects the thermal properties of the grounds, increasing (or decreasing) the grounds ability to store and transfer heat. Therefore, a thorough understanding of the local climate, soils type (particularly particle size) and moisture content can aid in designing the optimum ground loop configuration for a heat pump installation.

Generally, ground temperature behaviour can be categorised into three zones (e.g. Pouloupatis et al 2011),

1. the surface zone: where ground temperatures are sensitive to diurnal variations,
2. the shallow zone: where ground temperatures are sensitive to seasonal weather variations, and
3. the deep zone: where ground temperatures are near constant year-round.

The depth of these three zones are dependent on the thermal properties of the local soil.

This paper outlines the thermal properties of near-surface soil in New Zealand. Annual temperature variations are used to determine apparent thermal diffusivity of the ground.

2. DATA

Data used in this paper consists of data from two dedicated temperature monitoring boreholes and temperature profiles from a network of climate stations.

Borehole monitoring data comes from instrumented wells located at Wairakei (Taupo) and Lincoln (Christchurch), New Zealand (Figure 1). The *in-situ* temperatures are used to calculate apparent thermal diffusivity of the soils at both locations (van Manen and Wallin 2012; Seward and Prieto, 2018).

The Wairakei borehole is 7.5 m deep and was drilled in July 2010 (van Manen and Wallin, 2012). Ground temperatures have been continuously recorded at 31 depths every 15 minutes. The site also measures surface rainfall and air temperature.

The Lincoln borehole is 9.4 m deep and was drilled in 2014 (Seward and Prieto, 2018). Ground temperatures have been continuously recorded at 10 depths every 15 minutes. The site also measures surface rainfall and air temperature.

The *in-situ* temperatures are used to calculate apparent thermal diffusivity of the soils at both locations (e.g. Tabbagh et al 1999). Additionally, temperature profiles for the top 1m, recorded at 62 national climate stations (Black triangles in Figure 1) (NIWA 2018) are used to determine apparent thermal diffusivity for a variety of different soil types. Ground temperatures are recorded hourly at 10, 20, 50 and 100 cm depths.

2.1 Wairakei Borehole

The Wairakei borehole contains 31 sensors ranging from depths between the surface and 7.39 m. The lithology of the borehole is predominately unconsolidated pumice, with a small layer of soil on the top. Ground temperatures have been recording every 15 minutes since July 10, 2010. Figure 2 shows the 9 am recorded temperatures at selected depths (0.0, 0.4, 0.5. 0.8, 1.0, 1.3, 1.6, 2.0, 2.4, 3.1, 3.5, 4.4, 5.4, 6.4 and 7.4 m) up until September 2018. Seasonal variations are apparent in both temperature amplitude and seasonal phase delays at all sensors. Temperature variations (amplitude) decreases with depth, with ground temperatures becoming more stable at depths greater than 5 m. Seasonal phase delays are also evident by the changes in time of peak (and trough) temperatures with depth (Figure 2).

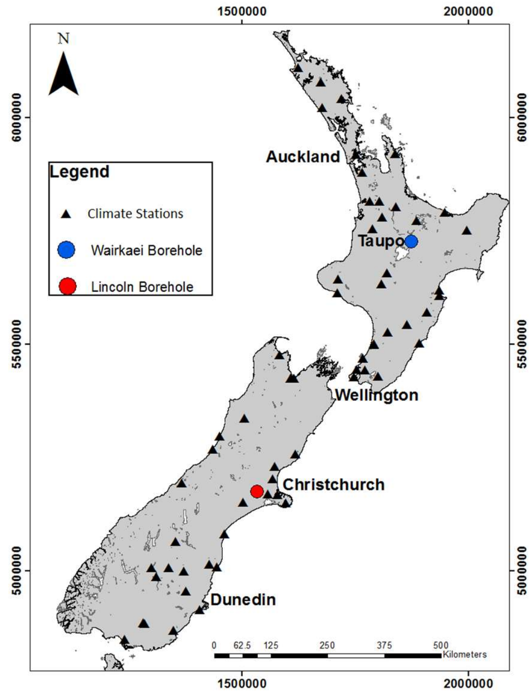

Figure 1: Location of ground temperature boreholes used in this study.

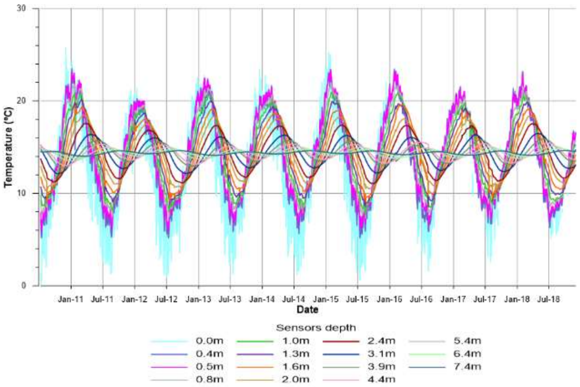

Figure 2: 9am temperature data recorded at different depths within the Wairakei borehole.

Figure 3, shows the ground temperature variation over the timespan of an average day for different seasons of the year. It is evident from this plot that the surface zone extends to a depth of approximately 0.5 m on any average day, regardless of the season. The seasonal zone appears to extend the full depth of the bore, with the bottom sensor (7.4 m) showing an annual temperatures variation of approximately 0.2 °C through the year. It can be assumed that the deep zone is likely to occur at a depth shallower than 10 m.

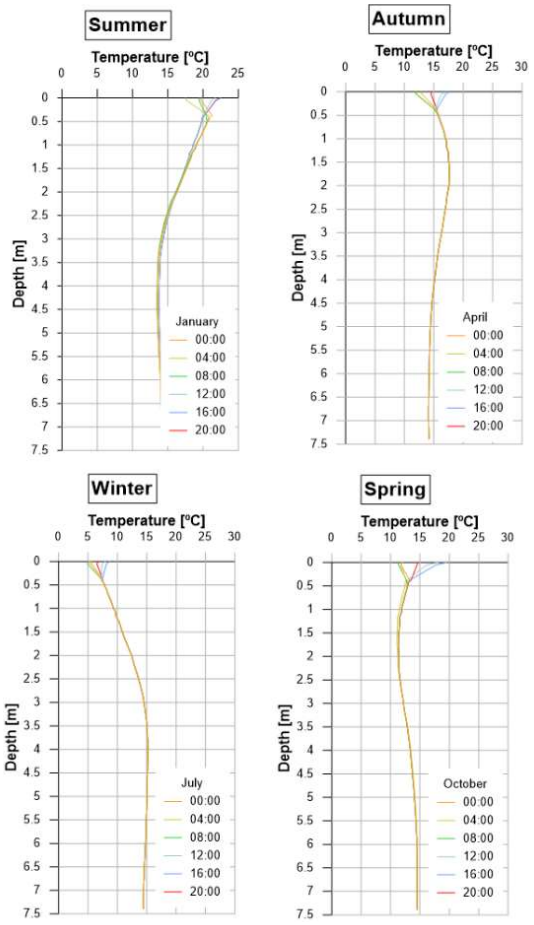

Figure 3: Seasonal temperature variations with depth

2.2 Lincoln Borehole

The Lincoln borehole contains 10 sensors ranging in depth from 0.4 m to 9.4 m. The borehole was drilled and sensors installed in December 2012, and terminated in February 2015 (Seward & Prieto, 2018). The lithology consists predominately of clay with course sandy gravel, overlain by silt. Figure 4 shows the recorded hourly temperatures at the 10 sensors located in the bore.

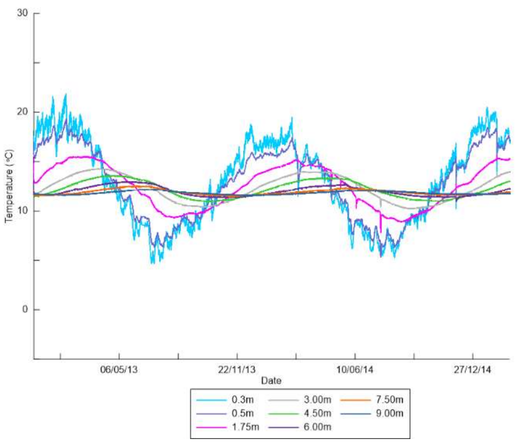

Figure 4: Recorded temperature data at different depths within the Lincoln borehole (image taken from Seward and Prieto 2018).

Daily and seasonal temperature variations, shown in Figure 5, suggests a surface zone of 0.5 m, and a seasonal zone to a depth of ~8 m. A deep zone is apparent at 9 m deep where the ground temperatures fluctuation is less than 0.05°C per year.

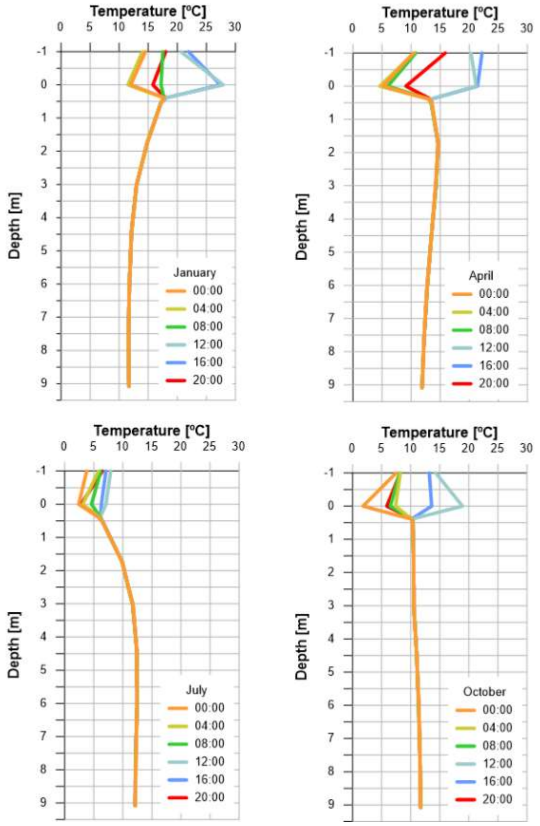

Figure 5: Seasonal temperature variations with depth within the Lincoln borehole. (image taken from Seward and Prieto 2018)

2.3 National 1m boreholes

The National Institute of Water and Atmosphere (NIWA) collects data from approximately 600 climate stations located around New Zealand. Monitored data includes air temperature (min, max), humidity, rainfall, windspeed, atmospheric pressure, sunshine hours etc. Shallow ground temperatures (measured at depths of 0.10, 0.20, 0.50 and 1.00 m) are measured at 62 of these sites every hour (Figure 1). As these boreholes exhibit annual variability in ground temperatures, an average of at least 5 years data is used to estimate the average temperature profile with depth seeking to more accurately determine the soil thermal properties.

3. THERMAL PROPERTIES

3.1 Determination of apparent thermal diffusivity

In-situ temperature measurements have been used to determine thermal properties, specifically the thermal diffusivity (α, m^2s^{-1}), which can be expressed as the ratio of thermal conductivity (κ, $Wm^{-1}K^{-1}$) and specific heat capacity (c_p, $Jm^{-3}K^{-1}$).

$$\alpha = \frac{k}{\rho c_p} \qquad (1)$$

Where ρ is the density ($m^2\ kg^{-2}$).

Thermal properties can be estimated by modelling measured ground temperatures at depth using an analytical solution to the one-dimensional heat conduction equation (Equation 2; Van Manen and Wallin, 2012):

$$\theta_{(z,t)} = \theta_m - \theta_A e^{\left(-z\sqrt{\frac{\pi}{T\alpha}}\right)} \cos\left(\omega\left(t_y - t_s - \frac{z}{2}\sqrt{\frac{T}{\pi\alpha}}\right)\right) \qquad (2)$$

where the boundary condition at the surface is described by a sinusoidal function with a period of *T* (365.25 days); θ_m and θ_A are the mean ambient temperature and mean amplitude of the ambient temperature (°C); *z* is depth (m); t_y is the Julian day of the year, t_s is the Julian day of the year that has the minimum ambient temperature, and ω is the angular frequency given by $2\pi/T$.

Alternatively, thermal diffusivity can be calculated using least squares inversion, by fitting an annually varying sine wave (Equation 3) to the recorded temperature data at different depths.

$$\theta_z = \theta_0 + \theta_A \sin(\phi) \qquad (3)$$

Figure 6 shows an illustration of a fitted sine curve for recorded data. This method allows anomalous ground temperatures to be removed, as well as accounting for unusual seasonal weather conditions.

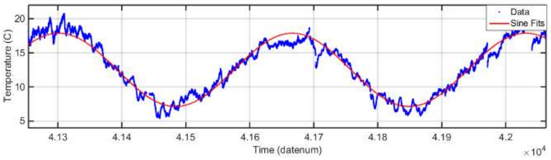

Figure 6: modelled sine wave fit of recorded ground temperature data from Lincoln borehole.

An average steady state temperature (θ_0), a maximum temperature variation (amplitude, θ_A) and a time delay (phase, ϕ) can be determined at different depths. The results from Equation 3 are used to calculate the apparent thermal diffusivity using differences in the phase (ϕ, Equation 4) and amplitude (θ_A, Equation 5) at different depths.

$$\alpha_\phi = \left(\frac{\omega}{2}\right)(z_2 - z_1)^2 \left(\frac{1}{(\phi(z_1) - \phi(z_2))}\right)^2 \qquad (4)$$

$$\alpha_A = \left(\frac{\omega}{2}\right)\left(\frac{z_2 - z_1}{\ln\left(|\theta_A(\omega, z_1)| \big/ |\theta_A(\omega, z_2)|\right)}\right)^2 \qquad (5)$$

where z_1 and z_2 are the selected depths. The thermal diffusivity calculated from the phase shift is thought to give a more accurate value (Tabbagh et al, 1999), although in a truly homogenous soil the results from equations 4 and 5 should be equal.

Equations 4 and 5 can be combined to give the relationship between amplitude damping and phase delay (Busby 2015).

$$\ln\left[\frac{\theta_A(\omega, z_2)}{\theta_A(\omega, z_1)}\right] = -\omega(|\emptyset(z_1) - \emptyset(z_2)|) \qquad (6)$$

Computed values for thermal diffusivity from the two monitored boreholes are included in Tables 1 and 2.

3.2 Laboratory measurements of thermal diffusivity

Soils samples from the Wairakei borehole were collected in the field using a soils sampling kit. Samples were analysed in the field using a KD2 pro needle probe (Decagon Devices 2014). These samples were then returned to a climate-controlled laboratory where further analysis on the raw, saturated and oven-dried samples were undertaken. These measurements were also undertaken using the KD2 pro needle probe.

Continuous core was extracted from the Lincoln borehole, during the drilling process. Samples of different lithologies from the core were extracted and analysed using a divided bar apparatus (Seward and Prieto, 2008; Antriasian, 2010; Antriasian and Beardsmore, 2014)).

No soils samples or cores were analysed from the 62 national network stations.

4. RESULTS

4.1 Apparent thermal diffusivity

For each the 62 national network sites the apparent thermal diffusivity was calculated.

Average ground temperature (θ_m), annual temperature fluctuation (θ_A) and phase delay (ϕ) at each sensor depth, were calculated from the available data using a Matlab code. From these values, thermal diffusivities of the soils between sensors were determined using equations 3 and 4 (Table A1). For example, thermal diffusivities were determined for depth intervals of between 0.20 – 0.50, 0.20 – 1.00 and 0.50 – 1.00 m. For every thermal diffusivity determination there is an amplitude and phase delay value. These are sometimes divergent, which is attributed to heat transfer that is not due to one-dimensional (vertical) conductivity flow (Koo and Song, 2008). Figure 7 shows the amplitude damping against the phase delay for all 300 values of thermal diffusivity determined from the 62 national network sites. The bold line shown on Figure 7 represents the one-dimensional conductive flow equation, with the two dashed lines showing a 5% deviation from equation 5. The amplitude and phase-shift thermal diffusivities that fall between the dashed lines are assumed to be where conductive heat transfer dominates. Values outside of these boundaries are thought to have external influencing factors, such as interactions with flowing groundwater, deep heating or other climatic effects.

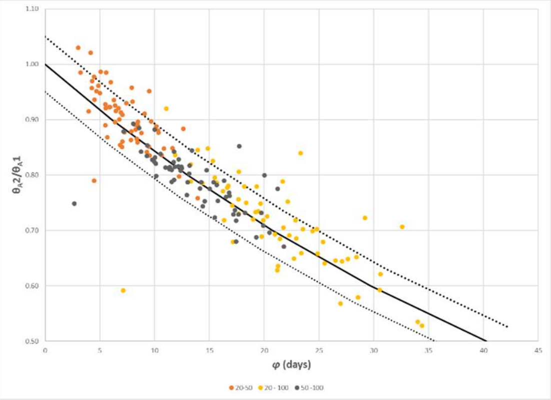

Figure 7: Plot of amplitude damping versus phase delay for 60 nationally operating ground temperature stations. The bold line represents the one-dimensional conductive heat transfer equation, with the dash lines indicating the 5% deviation.

Figure 8 compares the calculated apparent thermal diffusivities with the dominate soils types classified by the particle size. The four main soils types are Clay, Silt, Sand and Loam (Newsome et al., 2008). Sand is classified by particle sizes > 63µm, Silt by particle size > 2 µm and clays by particle sizes < 2 µm. A loam is generally a combination or mix of particles sizes. Results show that sand dominated soils have the greatest range of thermal diffusivity values, which is likely the result of a range of water saturation levels in the sandy soils. Silt has the smallest range of diffusivities, suggesting that these soils generally have a smaller range of saturation levels likely being fully saturated.

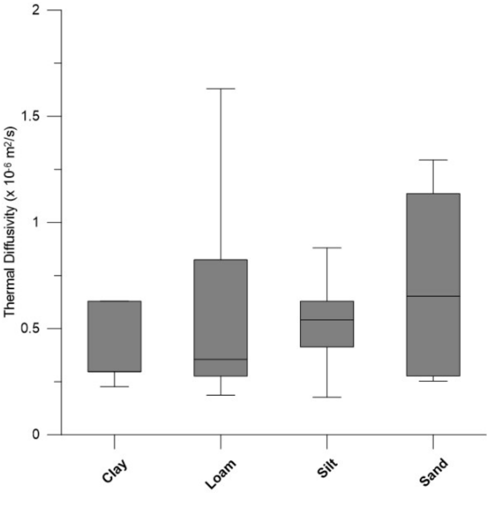

Figure 8: Apparent thermal diffusivity plotted again dominant soil type based on particle size.

Figure 9 shows the determined apparent thermal diffusivities of the near surface soils. The warmer yellow and red colours indicate areas of higher thermal diffusivity and are generally located in the South Island and the very north of the North Island. Lower apparent thermal diffusivities are seen in the central North Island, where the soils are predominately pumice or anthropic (Figure 10), and generally more porous material.

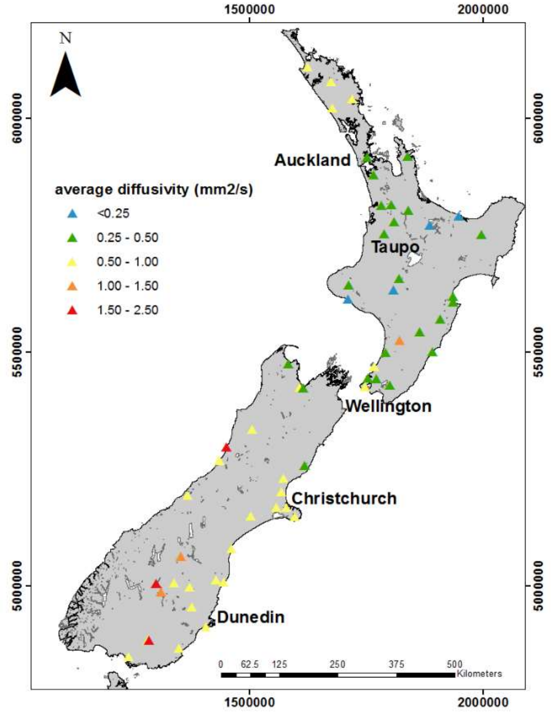

Figure 9: Average shallow thermal diffusivity determined at national network stations.

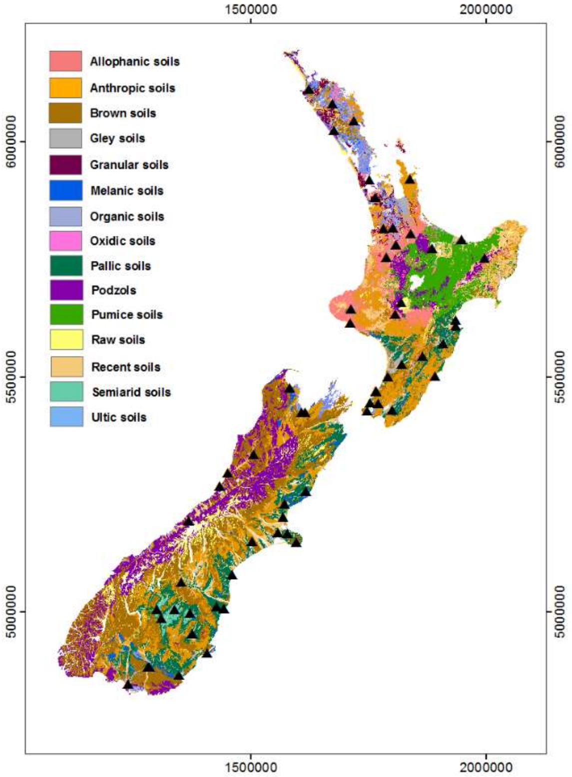

Figure 10: Dominate soil types present in New Zealand, with the black triangle indicating the locations of the shallow boreholes. Soils types are provided by Newsome et al (2008).

4.2 Measured thermal diffusivity

Thermal diffusivities, thermal conductivities and specific heat capacity have been determined from extracted cores retrieved from the Wairakei and Lincoln boreholes (Tables 1 and 2). The KD2 pro needle probe (Decagon Devices, 2014), used on the Wairakei soil samples, measures the thermal conductivity and thermal diffusivity, from which the specific heat capacity was determine using equation 1.

The divided bar method determines the thermal diffusivity and specific heat capacity (Antriasian, 2010; Antriasian and Beardsmore, 2014), from which the thermal conductivity is calculated using equation 1.

4.3 Comparison of method results

Measured thermal diffusivities are generally in agreement with those apparent thermal diffusivities determined from *in situ* ground temperature measurements, with measured values ranging between 0.17 to 0.56 mm^2s^{-1} for pumice soils at Wairakei compare well to the calculated apparent thermal diffusivities of between 0.12 and 0.4 mm^2s^{-1} (Figure 10).

Results from the Lincoln borehole also show close agreement between calculated apparent diffusivities ranging between 0.2 and 1.2 mm^2s^{-1} and measured values determine using the Divided Bar method ranging from 0.4 and 0.74 mm^2s^{-1} (Figure 11). There is a large range of calculated apparent thermal diffusivities using the phase delay method, compared to the results using the amplitude decay values. We assume this may result from interactions with the ground water table changing the saturation levels of the soils throughout the year. Further investigation is required.

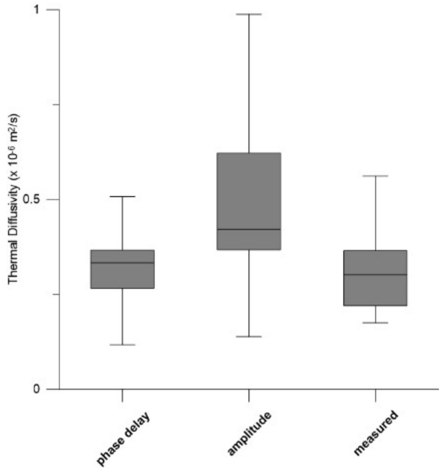

Figure 10: Apparent thermal diffusivity as calculated from in situ ground temperature measurements compared to measured KD2 pro values at Wairakei borehole.

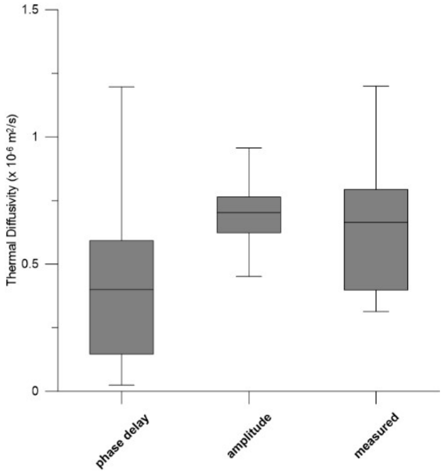

Figure 11: Apparent thermal diffusivity as calculated from *in situ* ground temperature measurements compared to measured electronic bar values at Lincoln borehole.

Table 1: KD2 pro needle probe thermal properties results from samples collected at the Wairakei borehole.

Sample ID	Depth (m)	Lithology	state	Diffusivity (α) (mm^2s^{-1})	Conductivity (κ) ($Wm^{-1}K^{-1}$)	Specific heat capacity (c_v) ($MJm^{-3}K^{-1}$)
W001	0.0	Top soil	Raw	0.204	0.505	2.891
			Saturated	0.175	0.626	3.077
			Dried	0.220	0.322	1.430
W002	0.25	Pumice soil	Raw	0.271	0.861	3.178
W003	0.50	Pumice soil	Raw	0.283	0.719	2.539
W004	1.00	Pumice soil	Raw	0.312	0.697	2.234
			Saturated	0.365	0.901	2.468
			Dried	0.335	0.422	1.256
W005	1.50	Pumice soil	Raw	0.313	0.749	2.391
W006	2.00	Pumice soil	Raw	0.220	0.285	1.299
			Saturated	0.562	0.669	2.524
			Dried	0.292	0.363	1.245

Table 2: Divided bar thermal properties results from samples collected at the Lincoln borehole.

Sample ID	Depth (m)	Lithology	state	Diffusivity (α) (mm^2s^{-1})	Conductivity (κ) ($Wm^{-1}K^{-1}$)	Specific heat capacity (c_v) ($MJm^{-3}K^{-1}$)
L001	0.0	Top soils	Raw	1.2	1.63	1.31
L002	0.50	Clay	Raw	0.62	0.84	1.35
L003	1.00	Sand grit clay	Raw	0.83	2.50	0.86
L005	2.00	Sandy clay	Raw	0.67	1.72	1.84
L006	4.50	Sandy clay with pebbles	Raw	0.75	1.63	1.37
L010	6.00	Sandy clay with pebbles	Raw	0.80	1.33	1.42

5. DISCUSSION

Combining the results from the 62 national network stations and two ground temperature monitoring boreholes at Wairakei and Lincoln, allows comparison of thermal properties with soils type and climatic conditions. Apparent thermal diffusivity results suggest that there is a distinction between the thermal properties of soils found in the North Island, and those found in the South Island.

Figure 12, shows the annual average 1m deep ground temperature. Comparison between Figure 8 and Figure 12, does not show a clear correlation between ground temperatures and thermal diffusivity values. This suggests that the local geology, soil type and moisture content are the main causes of varying thermal diffusivity in New Zealand, with annual temperature conditions having little effect on the thermal properties of the soils.

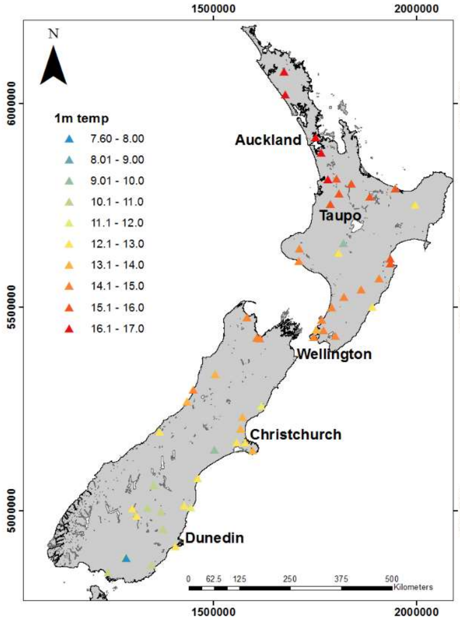

Figure 12: average annual 1 m deep ground temperatures.

The median thermal diffusivities for the sand, silt, clay and loam are 0.65, 0.54, 0.30 and 0.36 mm^2s^{-1}, respectively. Globally, the thermal diffusivity of clay can vary between 0.15 to 1.2 mm^2s^{-1}, with the key influence being moisture content (Busby, 2015; Abu-Hamdeh, 2003; Al Nakshabandi and Kohnke, 1965). A similarly large range is seen for sandy material, with diffusivities recorded between 0.6 and 1.6 mm^2s^{-1} (Busby 2015; Kappelmeyer and Haenel, 1974). Comparison with the global ranges for each soil type suggest that the values determined in this study for New Zealand soil types are within the global range with the range in calculated apparent thermal diffusivity for New Zealand soil types being general slightly lower than the global average.

It is known that the soil water content has a large influence on the thermal properties of a soil matrix (e.g. Busby et al., 2009). This is evident in the comparison of raw, saturated and oven-dried soil samples from the Wairakei Borehole (Table 1). The thermal diffusivity of a fully saturated pumice soils sample is almost twice that of a dried sample.

Temperatures and thermal properties of permeable soil materials are affected by rainfall. Figure 13 shows two examples of ground temperatures variations after rainfall events, with the rain cooling ground temperature in the winter months and warming them in the summer. This effect is predominately due to the air temperature to which the rain is acclimatise. The depth to which ground temperatures are affected is dependent on the volume of rainfall and pre-existing saturation level of the soil matrix (Abu-Hamdeh 2003). Further studies into the effects of ground water level, groundwater flow on ground temperatures might be useful in New Zealand to quantify these affects and their influence on horizontal ground loop design.

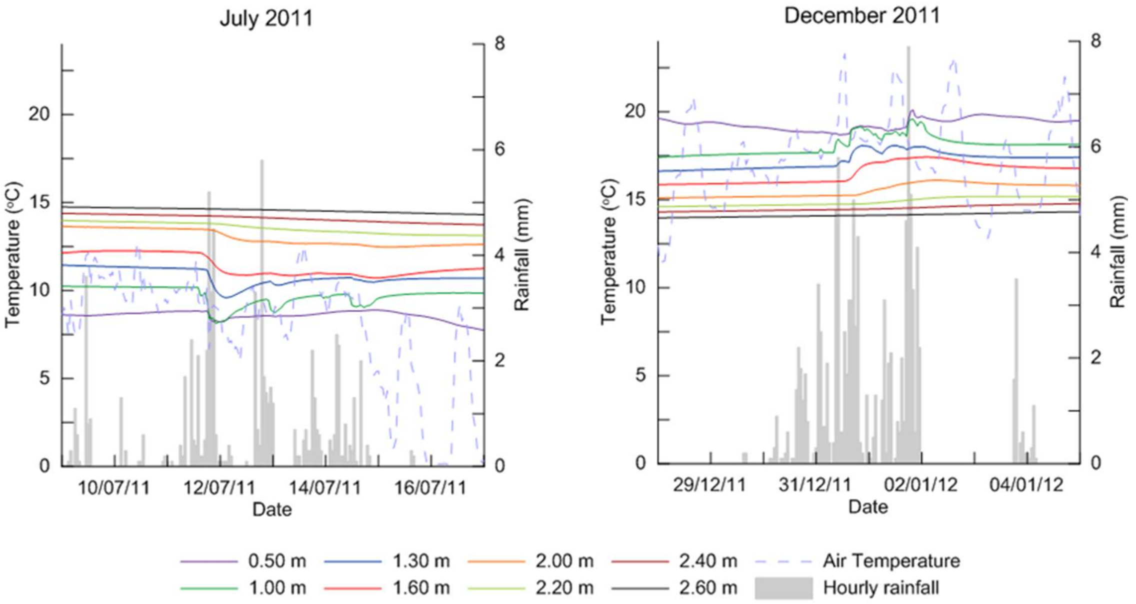

Figure 13: Two examples of the effects of rainfall on near-surface ground temperatures at Wairakei Borehole (extracted from Seward and Prieto 2015).

6. SUMMARY AND CONCLUSIONS

In this study, routinely collected soil temperature data from a national network, supplemented with temperature data from two boreholes is used to determine thermal properties of different New Zealand soils types. Using seasonal temperature cycles over a minimum of 5 years, thermal diffusivities are determined for each site for an average year, removing any uncharacteristic weather patterns. The calculated apparent thermal diffusivities are compared to laboratory measurements of thermal diffusivities of soil sample where these are available. It is seen that the determined apparent thermal diffusivities are in reasonable agreement with the measured thermal diffusivities. Median apparent thermal diffusivities for the sand, silt, clay and loam soil types are estimated to be 0.65, 0.54, 0.30 and 0.36 mm^2s^{-1} respectively. The saturation levels of these different soil types have a large influence on the thermal diffusivity and needs to be well understood for horizontal ground loop design in these environments. Future studies will look at quantifying these effects and the influences of ground water levels and flow.

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Table A1: summary of result for the 62 climate stations. Classifications of Particle size, Permeability, and Temperature class are provided by Newsome et al (2008). Average 1m temperatures are averaged over a minimum of 5 years, and Diffusivity values are calculated using Equations 4 and 5.

Station name	latitude	longitude	Particle size	Permeability	Temperature class *	Average 1m temperature °C	Diffusivity (amplitude) mm^2/s	Diffusivity (phase shift) mm^2/s
Akaroa Ews	-43.80938	172.96574	Silty	Moderate/Slow	MM	13.52	0.594	0.544
Akitio Ews	-40.57728	176.44889	Loamy	Moderate	MM	12.49	0.435	0.355
Appleby 2 Ews	-41.31727	173.09482	Loamy/Skeletal	Moderate/Rapid	MM	14.62	0.667	0.845
Auckland Motat Ews	-36.86297	174.71185	town	town	town	16.77	0.551	0.386
Balclutha, Telford Ews	-46.29282	169.7315	Silty	Slow	CM	10.95	0.844	0.605
Cheviot Ews	-42.8289	173.22386	Silty	Moderate/Slow	MM	11.39	0.433	0.413
Clyde 2 Ews	-45.20342	169.3182	Sandy	Rapid	DM	12.82	0.565	0.652
Cromwell Ews	-45.03392	169.1955	Sandy/Skeletal	Moderate/Rapid	DM	13.17	1.944	1.294
Dannevirke Ews	-40.20812	176.11026	town	town	town	14.62	0.344	0.502
Dargaville 2 Ews	-35.93145	173.85317	Sandy	Moderate	T	16.77	0.795	0.757
Diamond Harbour Ews	-43.63312	172.72808	Silty	Moderate/Slow	MM	13.06	0.548	0.549
Dunedin, Musselburgh Ews	-45.90129	170.5147	Clayey	Moderate/Slow	town	12.36	0.439	0.629
Franz Josef Ews	-43.36548	170.13428	Silty	Moderate	MM	13.01		0.842
Gore Aws	-46.115	168.887	Silty	Moderate/Slow	CM	11.16	0.433	0.498
Gore Ews	-46.12375	168.91938	Silty/Skeletal	Moderate/Rapid	CM	10.00	0.298	
Greymouth Aero Ews	-42.46022	171.19157	town	town	town	14.42	0.846	1.091
Hamilton, Ruakura 2 Ews	-37.77567	175.30506	Loamy	Slow	town	15.98	0.167	0.276
Hawera Aws	-39.6117	174.2917	Silty	Rapid	WM	14.10	0.190	0.201
Hokitika Ews	-42.71228	170.98428	Sandy	Rapid	MM	14.08		0.267
Invercargill Aero Aws	-46.413	168.317	Silty	Moderate/Slow	DM	11.06	0.249	0.269
Kaikohe Aws	-35.424	173.822	Loamy	Moderate/Slow	T	16.72	0.515	0.487
Kaitaia Ews	-35.135	173.262	Sandy	Slow	T	17.33	1.662	1.136
Lauder Ews	-45.0401	169.68419	Silty	Slow	DM	10.99	0.992	0.968
Levin Aws	-40.622	175.257	Loamy/Skeletal	Rapid	MM	15.11	0.490	0.819
Levin Ews	-40.62699	175.26193	town	town	town	14.97	0.594	0.598
Lincoln, Broadfield Ews	-43.62622	172.4704	Silty/Skeletal	Moderate/Slow	MM	12.67	0.586	0.696
Martinborough Ews	-41.25231	175.38985	Skeletal	Moderate/Rapid	MM	14.27	0.237	0.351
Matamata Hinuera Ews	-37.87683	175.73496	Silty	Moderate/Slow	MM	15.71	0.359	0.298
Middlemarch Ews	-45.51814	170.13561	Loamy	Moderate	CM	11.04	0.636	0.824
Motu Ews	-38.28566	177.52941	-	Moderate	WM	12.22	0.178	0.226
Mt Ruaperu, Chateau Ews	-39.1977	175.54491	Sandy	Rapid	-	10.00	0.227	0.277
Napier Ews	-39.49846	176.91189	town	town	town	16.57	0.411	0.343
Oamaru Ews	-45.05679	171.02261	Silty/Skeletal	Moderate/Slow	MM	11.87	0.555	0.629
Ohakune Ews	-39.41935	175.41258	Silty	Moderate	MM	12.18	0.156	0.177

Palmerston North Ews	-40.38195	175.60915	Loamy	Moderate	WM	15.04	0.731	0.832
Paraparaumu Aero Aws	-40.907	174.984	town	town	town	14.63	0.284	0.407
Paraparaumu Ews	-40.90392	174.98437	town	town	town	15.41	0.249	0.285
Porirua, Elsdon Park Aws	-41.12683	174.83531	town	town	town	16.04	0.589	0.649
Pukekohe Ews	-37.20637	174.86384	Loamy	Moderate	WM	16.25	0.266	0.280
Ranfurly Ews	-45.12427	170.10045	Silty/Skeletal	Moderate/Slow	DM	10.70	0.577	0.539
Rangiora Ews	-43.32858	172.61114	Silty	Slow	MM	13.45	0.759	0.974
Reefton Ews	-42.11578	171.86014	town	town	town	13.86	0.310	0.338
Richmond Ews	-41.32773	173.18615				14.79	0.308	0.395
Rotorua Ews	-38.14635	176.2578	Loamy	Rapid	town	15.72	0.497	0.210
Stratford Ews	-39.33726	174.30487	Loamy/Clayey	Rapid/Moderate	MM	13.66	0.255	0.215
Takaka Ews	-40.86364	172.80568	Loamy	Moderate/Slow	MM	14.36	0.382	0.187
Tara Hills Aws	-44.528	169.89	Loamy	Rapid	CM	11.05	1.481	1.629
Te Kuiti Ews	-38.33356	175.1534	town	town	town	15.91	0.383	0.373
Timaru Ews	-44.41052	171.25426	Silty	Moderate/Slow	town	12.85	0.455	0.605
Upper Hutt, Trentham Ews	-41.14027	175.04283	town	town	town	14.59	0.701	0.565
Waikeria Ews	-38.09468	175.3876	Silty/Clayey	Slow	-	16.15	0.448	0.315
Waipara West ews	-43.07026	172.65344	Silty	Moderate	MM	13.66	0.698	0.880
Waipawa Ews	-39.9515	176.61706	Silty	Moderate	CM	14.37	0.385	0.421
Wellington Kelburn Aws	-41.285	174.768	town	town	town	14.41	0.661	0.612
Whakatane Ews	-37.94815	176.96773	Loamy	Moderate	MM	15.52	0.210	0.212
Whakatu Ews	-39.60698	176.91148	Loamy	Moderate	WM	15.29	0.332	0.308
Whangarei Ews	-35.7444	174.32868	town	town	town	18.08	0.599	0.569
Whatawhata 2 Ews	-37.78832	175.06906	Clayey	Moderate	WM	15.98	0.339	0.297
Whitianga Ews	-36.82817	175.67231	Sandy	Rapid	T	17.35	0.256	0.253
Winchmore 2 Ews	-43.78916	171.79029	Silty	Moderate/Rapid	MM	11.47	0.869	0.469
Windsor Ews	-45.00829	170.82281	Loamy	Moderate	MM	11.98	0.611	0.484

* Temperature class

T – Thermic 15-22°C ; WM – warm mesic 11-15°C; MM – mild mesic 11-15 °C (< 60 day @ <5°C); CM - cool mesic 8-11°C; C – cryic < 8°C